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Research paper

Topology optimization of efficient and strong hybrid compliant mechanisms using a mixed mesh of beams and flexure hinges with strength control

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ABSTRACT

This paper presents a new topology optimization technique for the design of compliant mechanisms that are efficient in transferring motion, force, or energy while being sufficiently strong to resist yield or fatigue failure. Generally, flexure hinges are efficient in transferring motion, force, or energy but are weak in resisting yield or fatigue failure while slender beams are relatively inefficient but strong. Thus, our philosophy is that a compliant mechanism may benefit from the above complimentary properties of flexure hinges and slender beams if they are connected and sized in a rational way. This requires a design approach with both flexure hinges and beams as constructional elements, and the design approach should include criteria on both efficiency and strength. Therefore, in the proposed technique, a mixed mesh of flexure hinges and beams was employed to discretize the design domain, and their connectivity, locations, and sizes were simultaneously determined to fulfill both the so-called stiffness-flexibility criterion (for efficiency) and a newly proposed input stroke criterion (for strength). The input stroke of a compliant mechanism, defined per the von-Mises yield criterion, is inversely proportional to the maximum stress per input displacement and represents the mechanism's maximum input displacement before yield failure. Both theoretical explorations and design examples demonstrate that the strength of compliant mechanisms can be significantly improved without compromising the efficiency, and trade-off designs that are better balanced between strength and efficiency can be obtained.

1. Introduction

A compliant mechanism (CM) gains at least part of its mobility from the deformation of its flexible components [1]. CMs have advantages such as reduced cost (reduced parts, simplified fabrication process, and reduced maintenance) and improved performance (less friction, improved precision, and improved adaptiveness). CMs have been utilized in various applications such as precision stages [2–4], MEMS [5], and biomedical devices [6,7].

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Similar to rigid-body mechanisms, CMs are used to transfer motion/force/energy. However, the performance of CMs is inherently limited because (1) they require a fraction of the input energy to deform parts, thereby reducing the efficiency in transferring motion/force/energy; (2) they are prone to yield or fatigue failure due to the deformation of components. Thus, it a challenge to design CMs that are efficient in transferring motion/force/energy and meanwhile being strong enough to resist failure. The goal of this study was to tackle this challenge.

A widely used synthesis approach to CMs is topology optimization (TO) [8]. Many research efforts to optimization schemes [8,9], analysis approaches [10], discretization schemes [11–14], and numerical difficulties [15–17] in topology optimization have been devoted. In TO, CMs are traditionally designed based on a stiffness-flexibility criterion [8]. This criterion has been formulated into many optimization formulations, such as the ratio of mutual strain energy to strain energy, mechanical advantage (*MA*), geometric advantage (*GA*), and mechanical efficiency (*ME*). These formulations, despite different forms, all result in lumped CMs [18] or CMs with undesirable point flexures [8] that are efficient in transferring motion, force, or energy but suffer from localized high stress (weak in resisting failure). Many strategies have been developed to avoid lumped CMs (or CMs with point flexures) [19,20] and to get more distributed CMs which generally exhibit lower stress levels than lumped CMs [21,22]. Krishnan et al. [23] also quantified the distribution of compliance as a metric to facilitate the size optimization of distributed CMs. However, distributed CMs are generally less efficient in transferring motion, force, or energy than CMs with flexure hinges. In contrast, flexure hinges are efficient in transferring motion/force/energy but are weak in resisting failure while beams are inefficient in transferring motion/force/energy but are strong in resisting failure Thus, our philosophy is that a compliant mechanism may benefit from the above complimentary properties of flexure hinges and slender beams if they are connected and sized in a rational way. A CM with properly connected and sized beams and flexure hinges may be more efficient in transferring motion/force/energy and meanwhile stronger in resisting yield/fatigue failure (with relatively low stress). However, if stress is not controlled in the optimization formulation, the obtained CMs will have unfavorable extremely high stress when loaded due to the stress concentration effects with flexure hinges [28]. Thus, we shall present a new TO framework for hybrid CMs with control over stress, and the goal of this study was to obtain trade-off designs that are both efficient and strong by taking advantages of the inherent complementary properties of flexure hinges and beams in terms of motion/force/energy transfer efficiency and stress distribution. This goal was achieved through a proposed design criterion (detailed in Section 2) for stress control, and the stress was accurately predicted through a super flexure hinge finite element with the consideration of stress concentration effects in flexure hinges.

Overall, with this new TO technique, hybrid CMs are designed with a mixed mesh of flexure hinges and beams, and the connectivity, locations, and sizes of both flexure hinges and beams are simultaneously determined to fulfill the criteria on stress, stiffness, and flexibility. The obtained CMs, therefore, may benefit from the complementary properties of these two types of components and thus be both efficient and strong.

In the following, the design criterion for stress control is presented in Section 2. In Section 3, the stress analysis of flexure hinges is detailed with consideration of stress concentration effects, based on the super flexure hinge element developed in our previous study [24]. The element is also verified through simulations using ANSYS. In Section 4, the effects of the location and size of a flexure hinge in a simple CM are investigated. In Section 5, the proposed TO technique is overall presented. Section 6 presents six design tests for compliant displacement amplifiers, and geometrically nonlinear finite element analysis was performed to verify the results. Section 7 concludes the paper.

2. Input stroke design criterion

Generally, TO is implemented with given input forces, and if yield failure is concerned, the maximum stress is kept not greater than the strength of the material [25]. However, in this study, we were not only interested in the maximum stress but also the displacement when the CM reaches this maximum stress. Specifically, the ratio of the maximum stress to the input displacement should be minimized to generate CMs that bear less stress per input displacement:

$$\text{Minimize } \sigma_{v,max}/u_{in} \tag{1}$$

where $\sigma_{v,\,max}$ and u_{in} are the maximum von-Mises stress and the input displacement, respectively, of a CM under specified input forces. This formulation gives preference to CMs that have relatively larger input motion range with lower stress levels.

The above idea can be implemented in an equivalent way:

$$\text{Maximize } U_{in,\ s} = \frac{\sigma_y}{\sigma_{v,max}/u_{in}} = \frac{\sigma_y}{\sigma_{v,max}} u_{in} \tag{2}$$

where σ_y is the yield strength of the selected material, and it is a constant which has no effect on optimization results. With σ_y in the formula, $U_{in,s}$ is inversely proportional to the maximum stress per input displacement and represents the input stroke (maximum allowable input displacement) of the CM before yield failure, and thus the functional requirement on $U_{in,s}$ is named as the input stroke criterion. Maximizing $U_{in,s}$ is equivalent to minimizing the ratio of the maximum von-Mises stress to the input displacement. A CM with a larger input stroke (or lower stress per input displacement) can withstand relatively larger deformation, more uncertain or critical loading conditions (e.g., cyclic loads resulting in fatigue failure), and has a larger operating room for actuators and therefore has better actuator usage and improved dexterity. The purpose of using $U_{in,s}$ is to indicate how the strength of the material is efficiently utilized for the mobility of CMs. Note that